

Exploring the Parameter Space of Europa's Ocean Salinity Through Time



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*Europa Clipper: MAss Spectrometer for Planetary EXploration (MASPEX)

§NASA Habitable Worlds, Vital Signs: Seismic Investigation of Icy Ocean Worlds : 16-HW16_2-0065

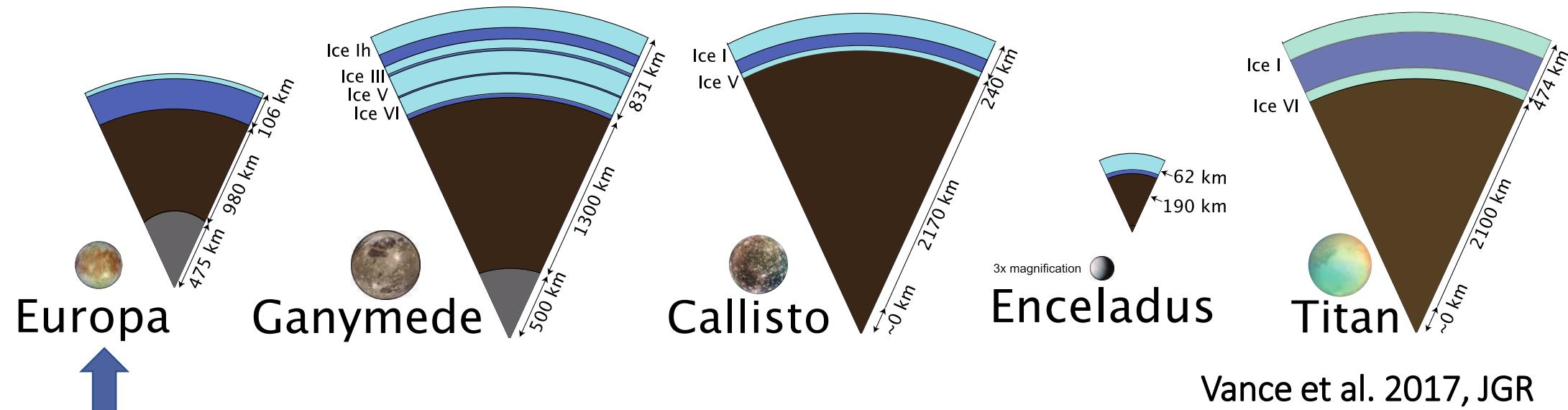
¥NASA Astrobiology Institute, Icy Worlds: 13-13NAI7_2-0024

^KPL Research and Technology Development Fund

Support

Thermodynamically consistent internal structures for icy ocean worlds

Prediction of measurable properties:
*compositional, isotopic, seismic, gravitational, tidal, electrical**



Focus of this talk
↑

Vance et al. 2017, JGR

Previous work

Sensitivity of interior structure solution to compositions of **ocean** and **ice**

Accounting for ***rock mineralogy, temperature profiles, and core size***



Vance et al. 2017, JGR - PlanetProfile
follows Cammarano et al. 2006

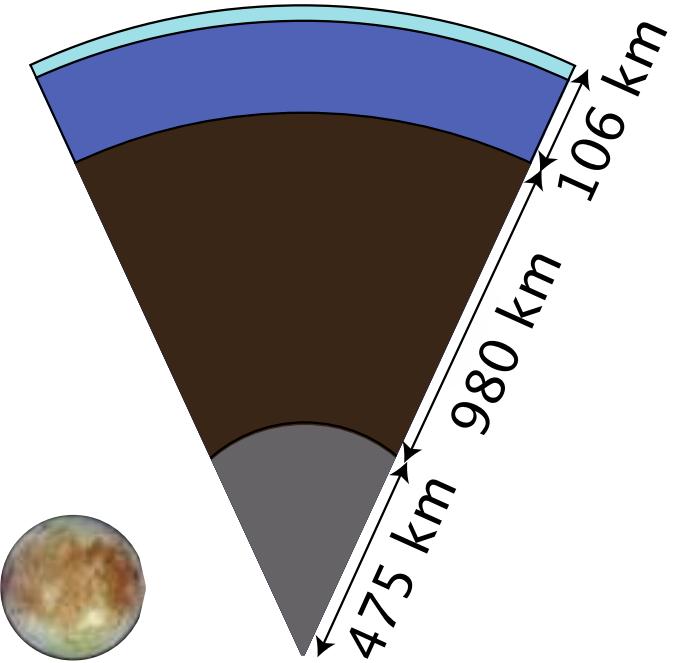


This work

Sensitivity of ocean composition to formation and evolution conditions

Accounting for

bulk mineralogy (starting materials)
partitioning of H_2O , Fe, S;
loss and addition of material through time

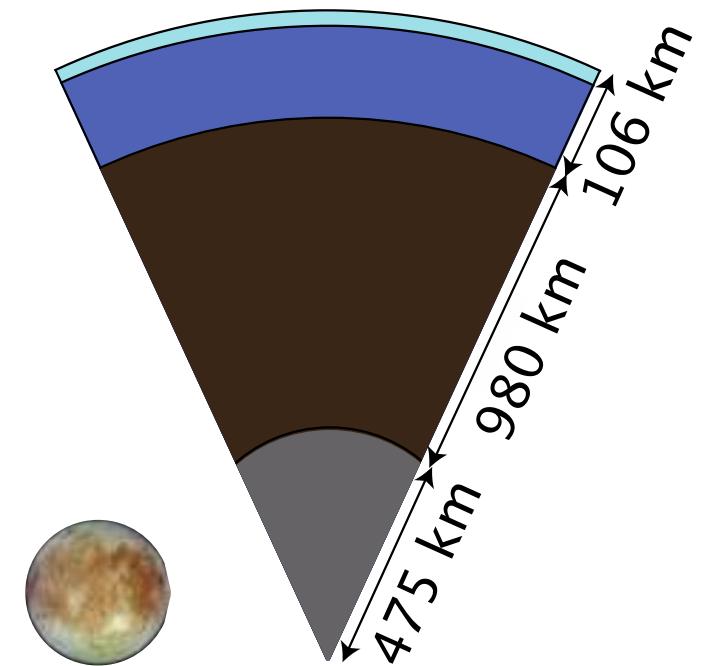
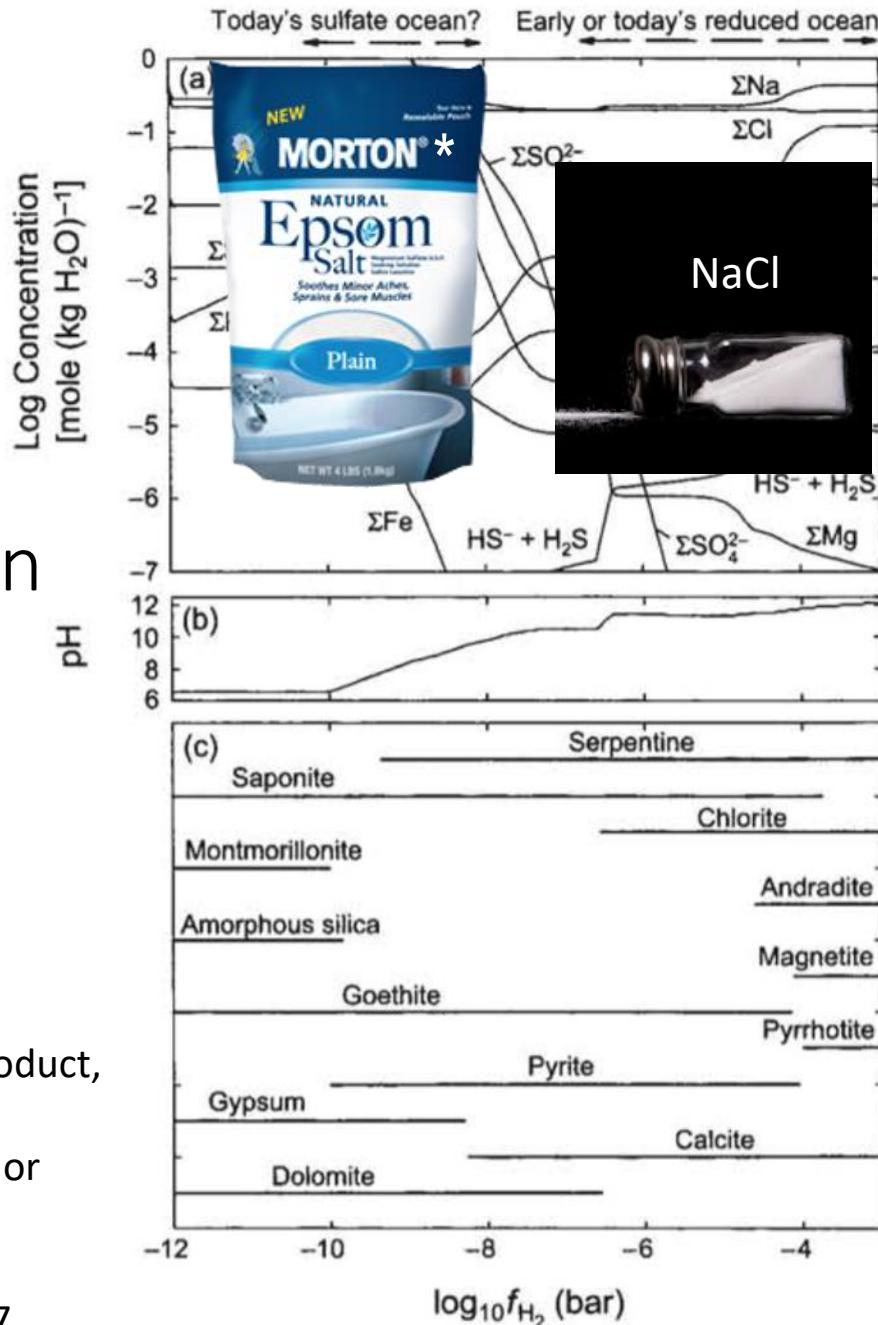


*follows Kuskov and Kronrod 2001
Zolotov and Shock 2001*

Ocean composition

Vance et al., Europa's Salinity Through Time, LPSC 2018, Woodlands

- is thermal evolution integrated through time
- depends on the oxidation state of the ocean



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PlanetProfile:

$$C = \int_M x^2 dm = \int \int \int r^4 \rho(r, \theta, \psi) \sin^3(\theta) dr d\theta d\psi$$

$$M_{iron} = M - M_{H_2O} - \frac{4\pi}{3} \rho_{sil} (R_{sil}^3 - R_{iron}^3)$$

$$R_{iron} = \left(\frac{M - M_{H_2O} - \frac{4\pi}{3} \rho_{sil} R_{sil}^3}{\frac{4\pi}{3} (\rho_{iron} - \rho_{sil})} \right)^{1/3}$$

$$C = C_{H_2O} + \frac{8\pi}{15} (\rho_{sil} (R_{sil}^5 - R_{iron}^5) + \rho_{iron} R_{iron}^5)$$

Sulfur: $\rho_{iron} = \frac{\rho_{Fe}\rho_{FeS}}{X_{FeS}(\rho_{Fe} - \rho_{FeS}) + \rho_{FeS}}$



Ocean thermodynamics*, (uniform w): EOS for **seawater**, **MgSO₄ (aq)**, **NH₃ (aq)**

McDougall 2011, Vance and Brown 2013, Vance et al. 2014, Tillner-Roth and Friend 1997

Vance et al. 2017, JGR

Rock thermodynamics: Gibbs energy minimization using Perple_X

Connolly et al. 2011

Core thermodynamics: fcc iron and FeS as per Cammarano et al. 2006

Europa	Enceladus	Ganymede	Callisto	Titan	if including an Fe core				
Inputs	R	ρ	C/MR^2	T_o	T_b	w	Q	ρ_{Sil}	ρ_{Fe}
	Radius	Bulk Density	Gravitational Moment of Inertia	Surface Temp.	Ice I bottom Temp.	Ocean Salinity	Mantle Heat	Silicate Mantle Density	Iron Core Density

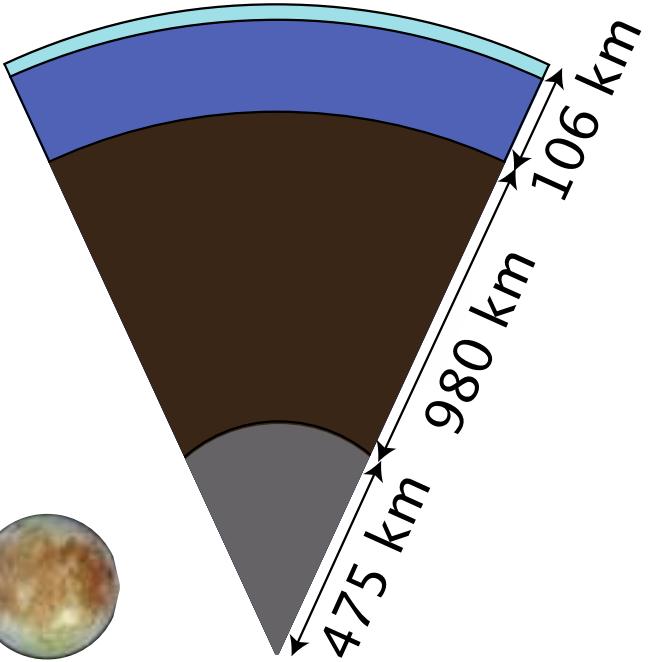
For Europa,

$$R = 1565 \pm 8 \text{ km}$$

$$C/MR^2 = 0.346 \pm 0.005$$

$$\rho = 2989 \pm 45 \text{ kg m}^{-3}$$

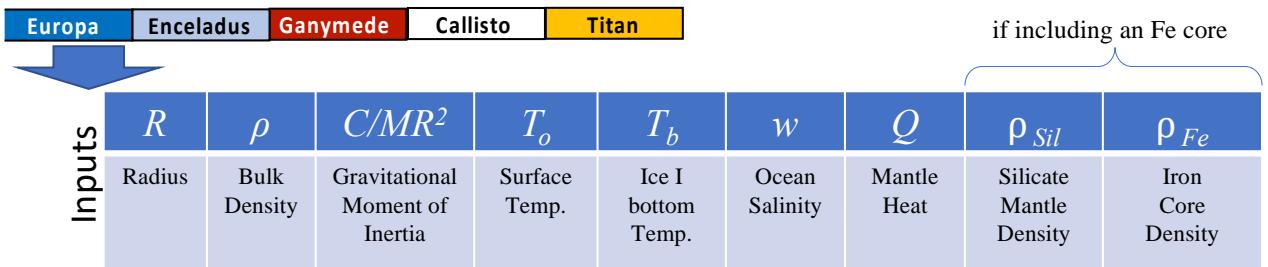
(Anderson et al. 1998)



PlanetProfile:

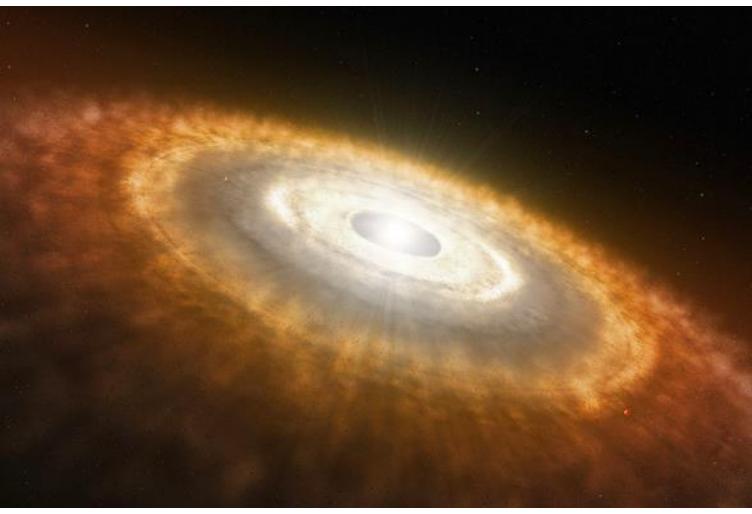
thermodynamic modeling linking
geophysics and habitability

github.com/vancesteven/PlanetProfile
Vance et al. JGR 2017.

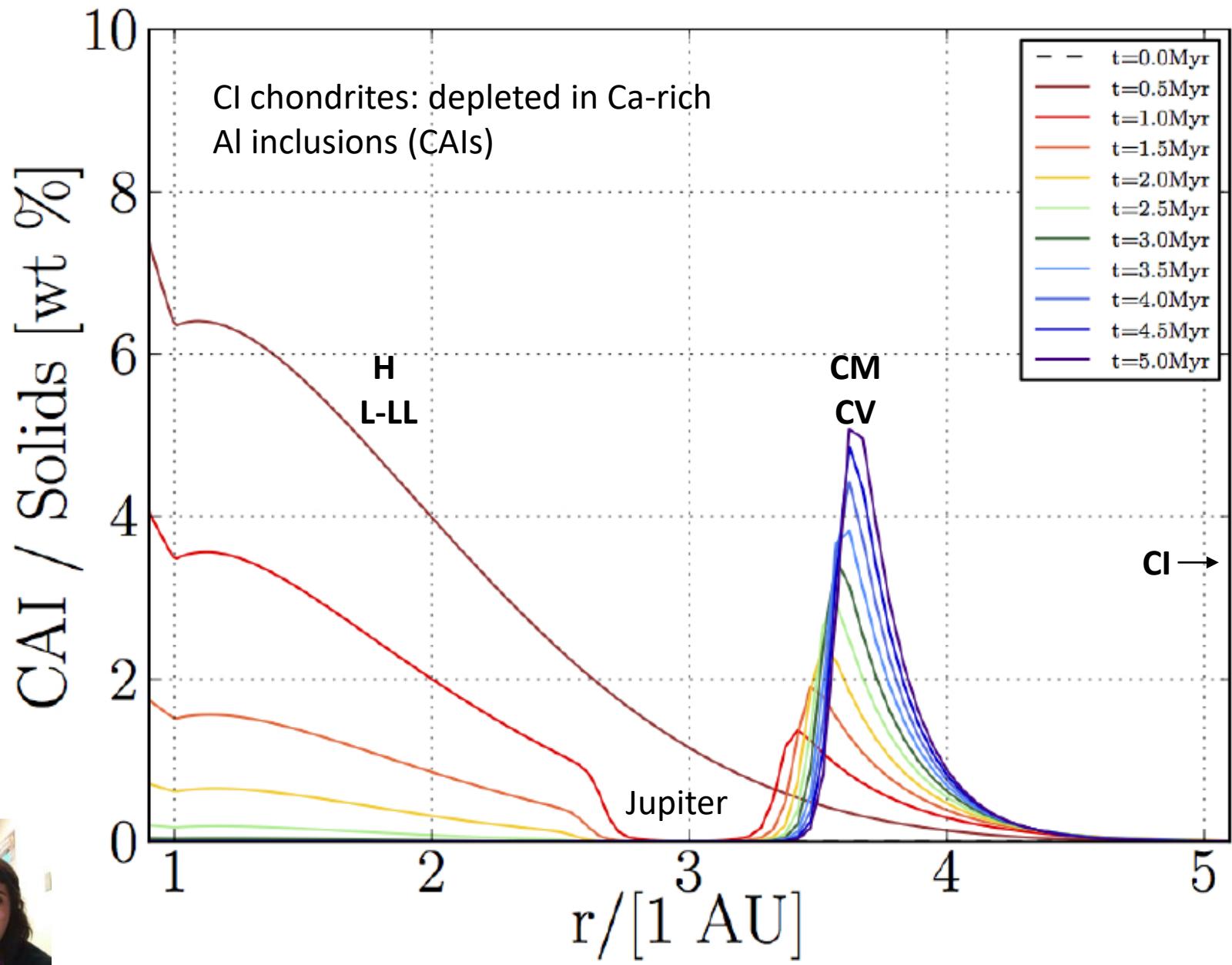


Accounting for bulk internal structure

	carbonaceous			ordinary			
	CI	CM2	CV3	H	L	LL	
SiO_2	22.69	28.97	34.00	36.60	39.72	40.60	
Al_2O_3	1.70	2.17	3.22	2.14	2.25	2.24	Kuskov and Kronrod 2001
FeO	4.63	22.14	26.83	10.30	14.46	17.39	
MgO	15.87	19.88	24.58	23.26	24.73	25.22	Adopted by Cammarano et al. 2006
CaO	1.36	1.89	2.62	1.74	1.85	1.92	Vance et al. 2017
Na_2O	0.76	0.43	0.49	0.86	0.95	0.95	
K_2O	0.06	0.06	0.05	0.09	0.11	0.10	
P_2O_5	0.22	0.24	0.25	0.27	0.22	0.22	
Fe(m)	0	0.14	0.16	15.98	7.03	2.44	
FeS	9.08	6.76	4.05	5.43	5.76	5.79	
C	2.80	1.82	0.43	0.11	0.12	0.22	



ESO/L. Calçada



Accounting for bulk internal structure

May have formed nearest to Jupiter (Desch et al. 2017 arXiv:1710.03809)

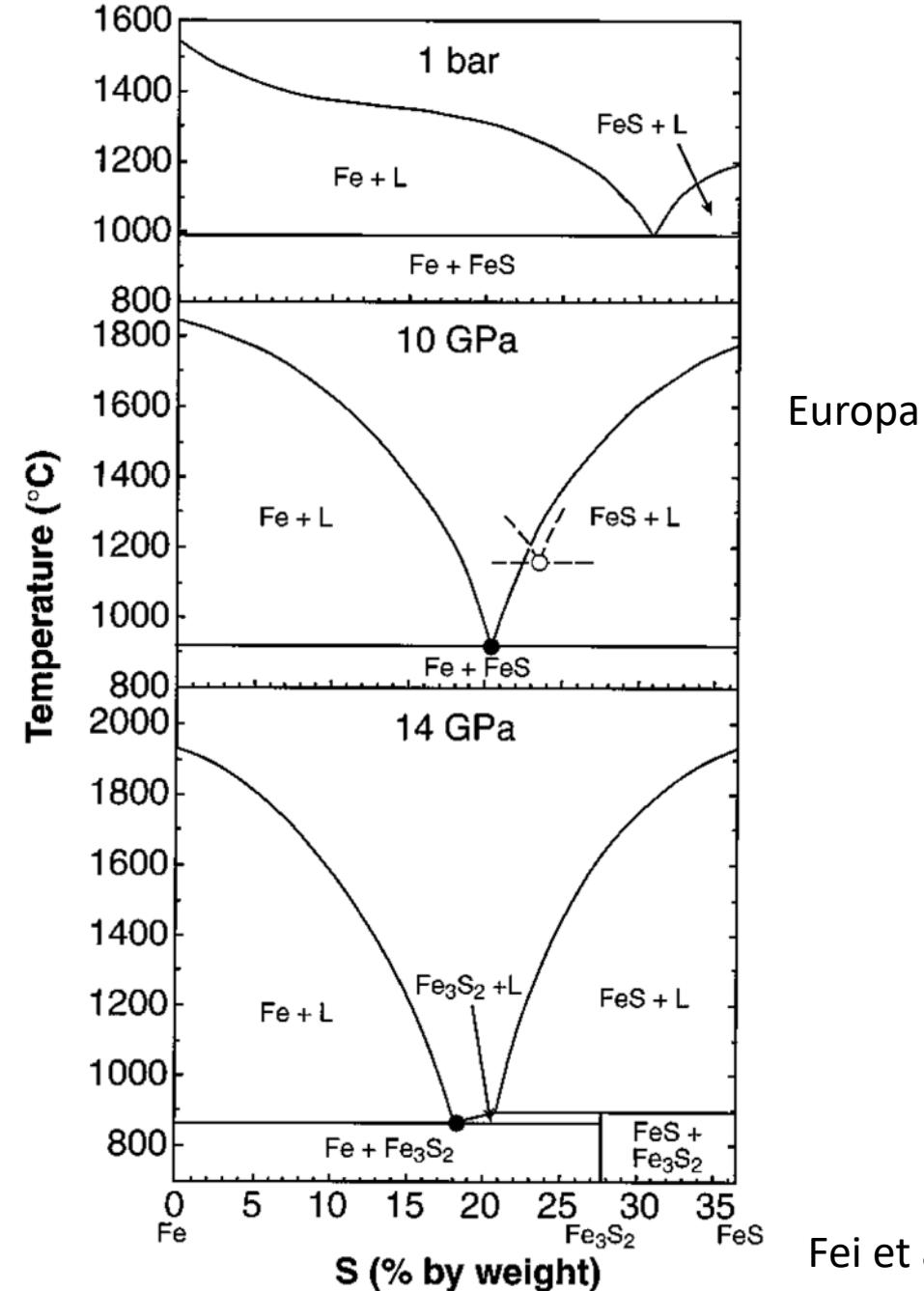
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Sulfur

- How much can go into the core?
- Earth's core may contain 2wt% S

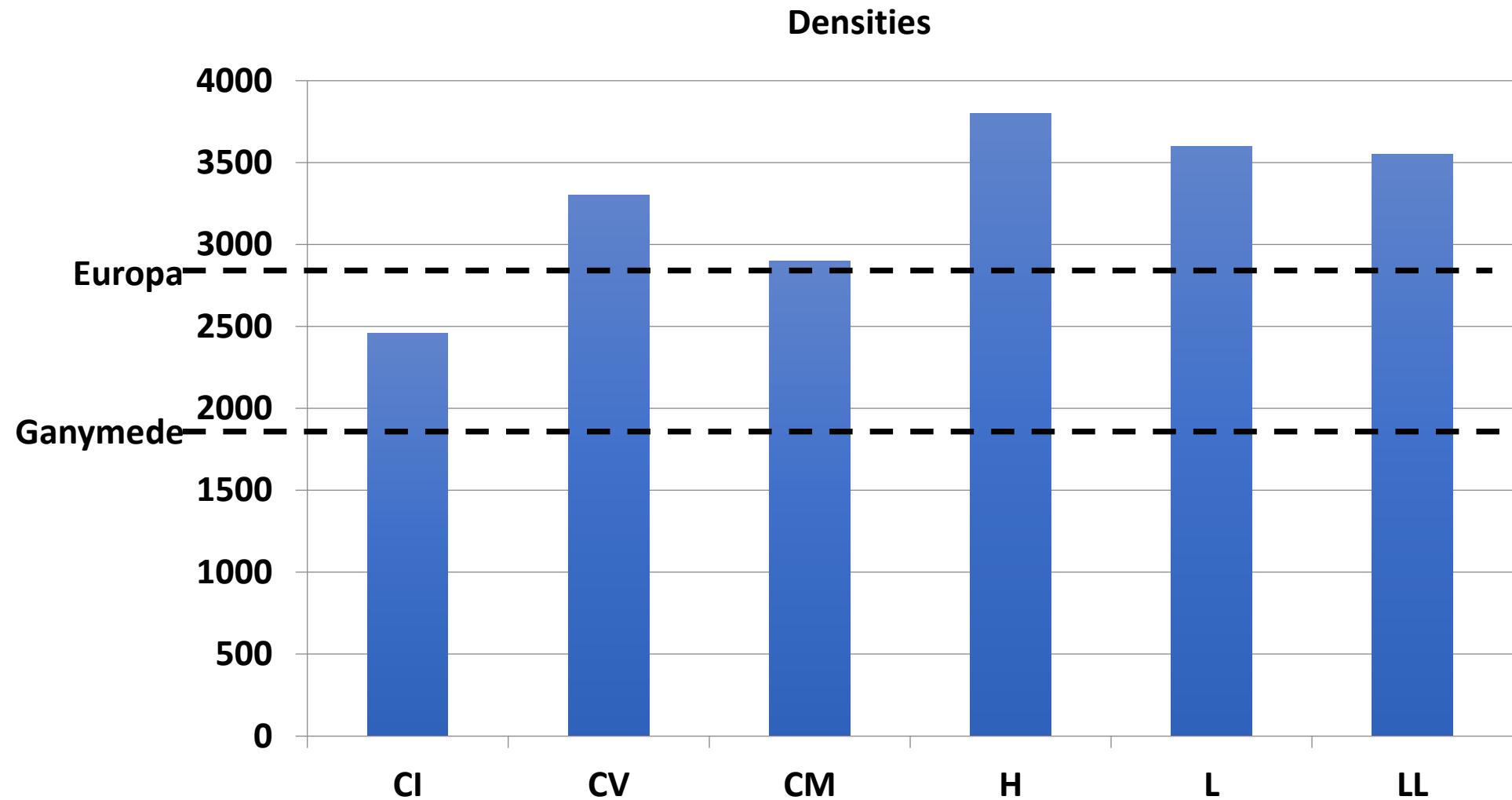
Savage et al. 2016

- Assume all iron from Fe(m) and FeS goes into the core
- Assume Fe-FeS system reaches 10wt% S

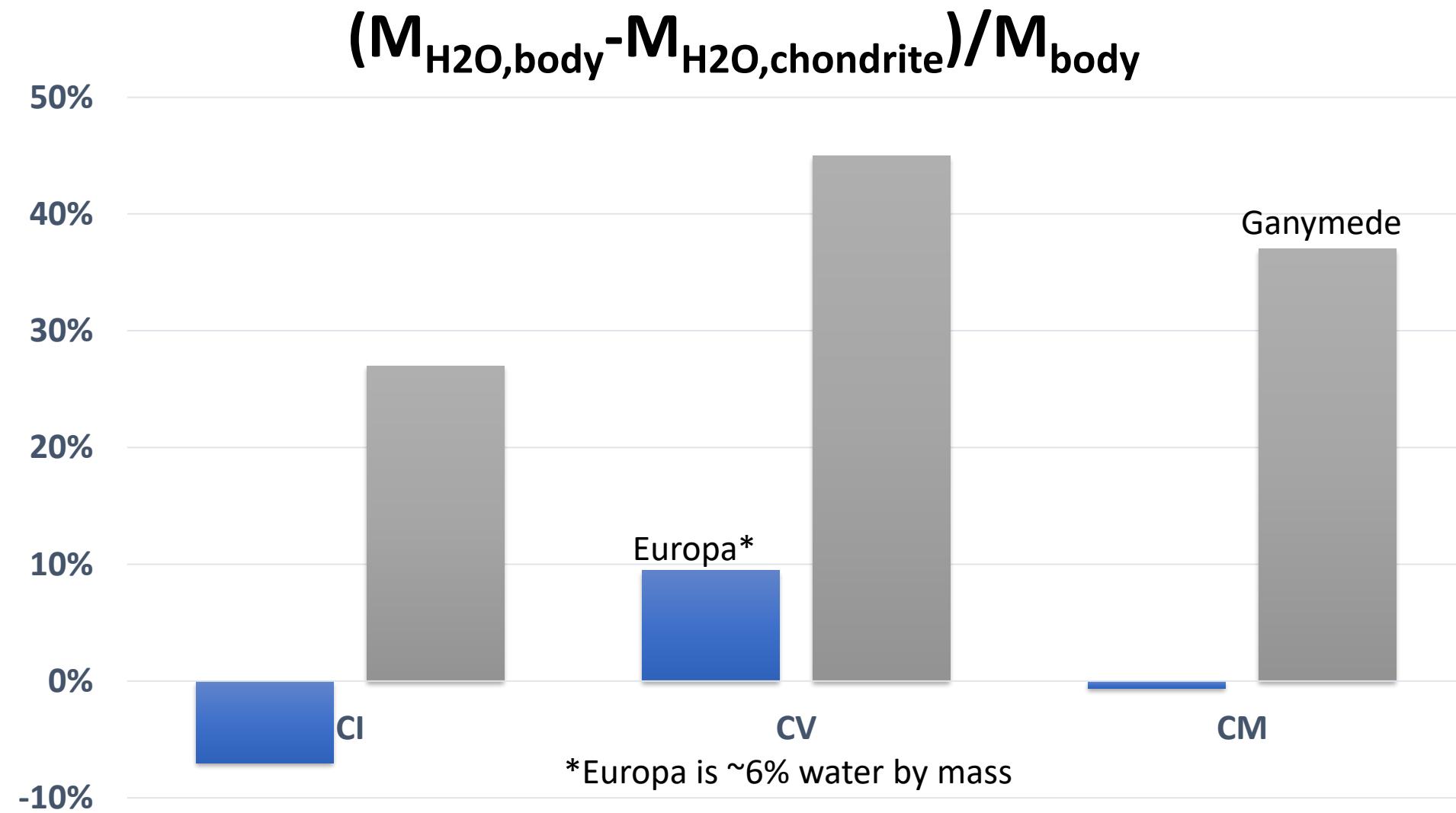


Fei et al. 1997

Water



Missing Water



Europa's formation from chondrites

	CI	CM2	CV3	H	L	LL
SiO_2	22.69	28.97	34.00	36.60	39.72	40.60
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CaO	1.36	1.89	2.62	1.74	1.85	1.92
Na_2O	0.76	0.43	0.49	0.86	0.95	0.95
$D_{\text{ice}} \text{ (km)}$	31	31	31			
$D_{\text{ocean}} \text{ (km)}$	122	121	122			
$R_{\text{rock}} \text{ (km)}$	1408 ± 15	1409 ± 15	1408 ± 15			
$R_{\text{core}} \text{ (km)}$	397 ± 141	410 ± 130	397 ± 141			
S in core (wt %)	7.3	7.3	7.3			
Excess H_2O (wt %)	7.1	0.6	-9.5			
Excess S (wt%)	3.0	2.1	2.2			

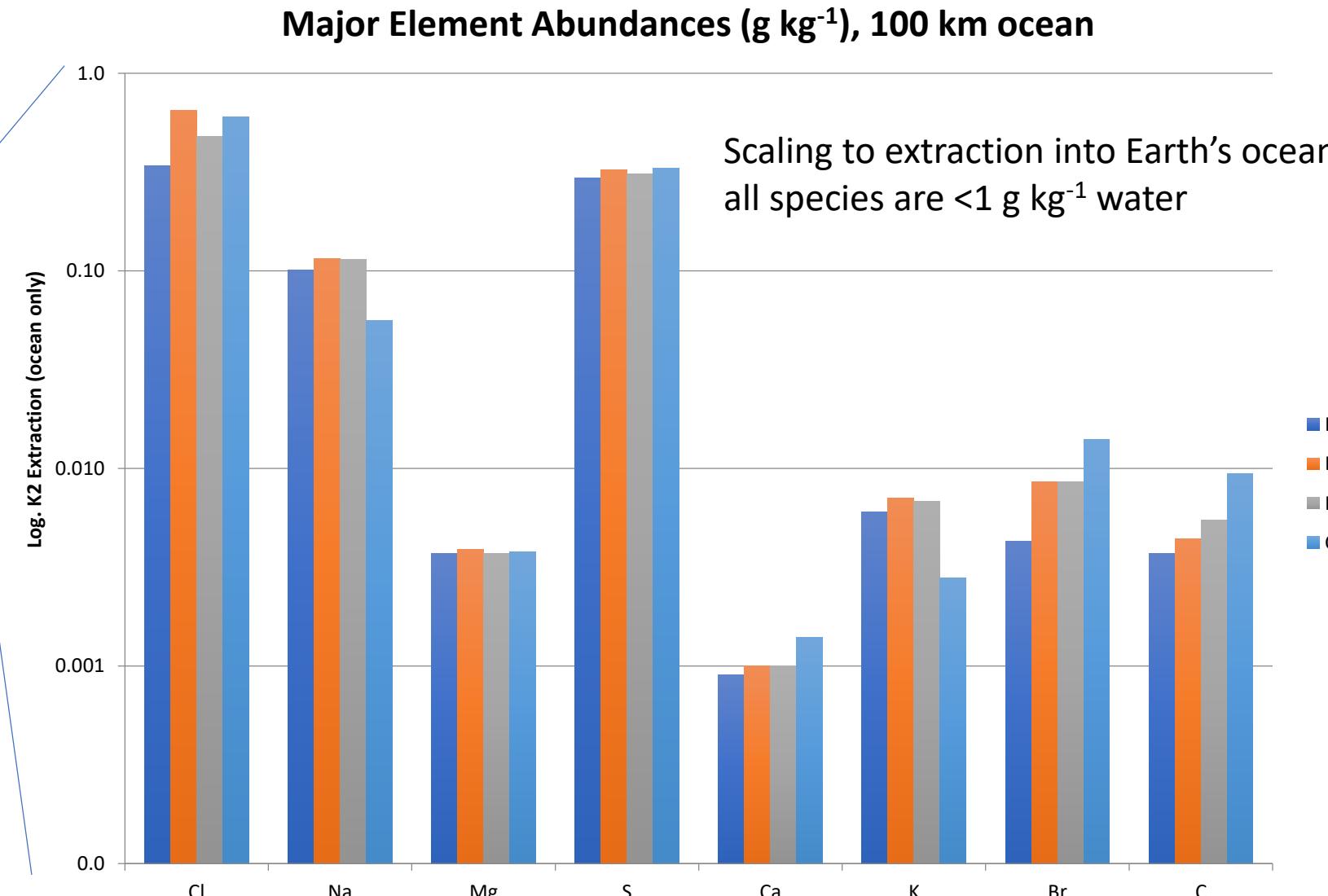
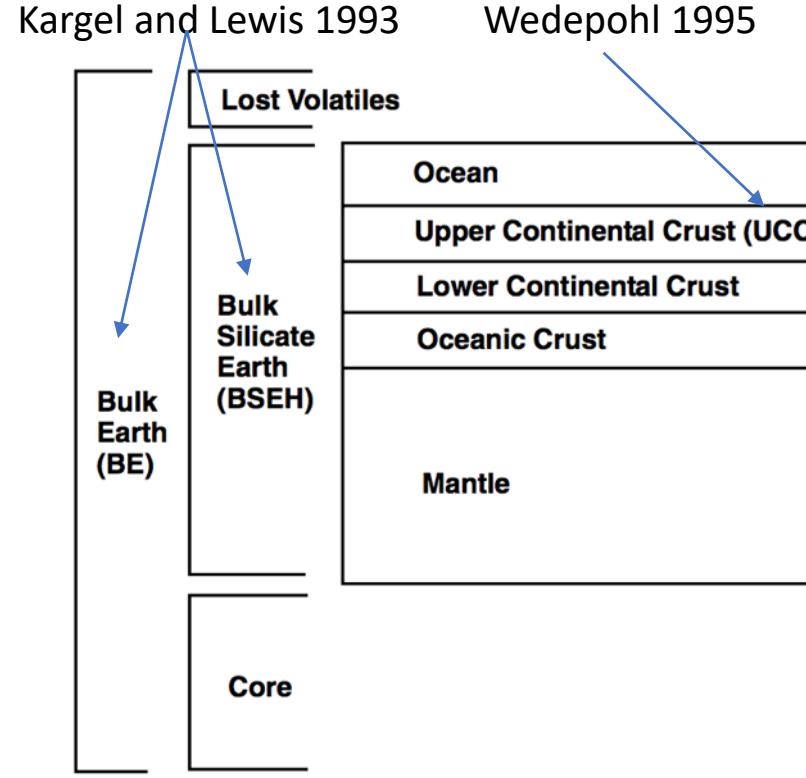
Salts

Total extraction into a 100 km ocean

Element (g kg ⁻¹)	CV	CM	CI	H	BSEH	Earth
Cl	3.2	5.5	9	1.8	0.47	19
Na	44	50	62	79	38	11
Mg	1800	1500	1200	1800	2800	1.3
S	280	350	700	260	3.5	0.9
Ca	240	170	120	160	320	0.41
K	4.6	4.8	7.1	10	3	0.4
Br	0.021	0.039	0.045	0.0064	0.00045	0.067

Zolotov and Shock 2001

Extraction of Soluble Ions into the Ocean



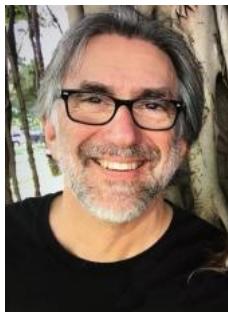
Conclusions

- Europa cannot have formed from CI chondrites
- If it formed from CM chondrites
 - the water must have been lost during formation
 - or, maybe it's locked up in the rock....
- If it formed from CV, it must have accreted its water from elsewhere
- There's plenty of S for oceanic SO_4

Co-authors:



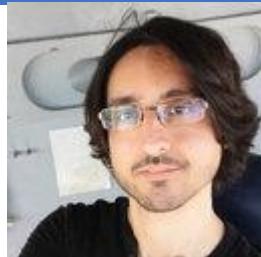
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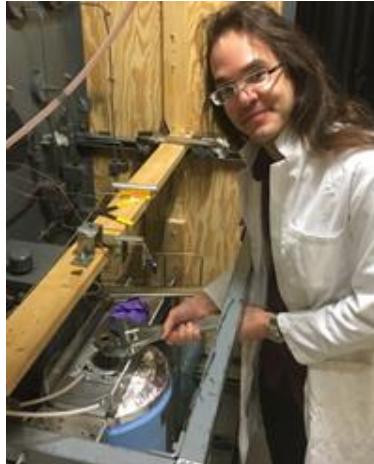
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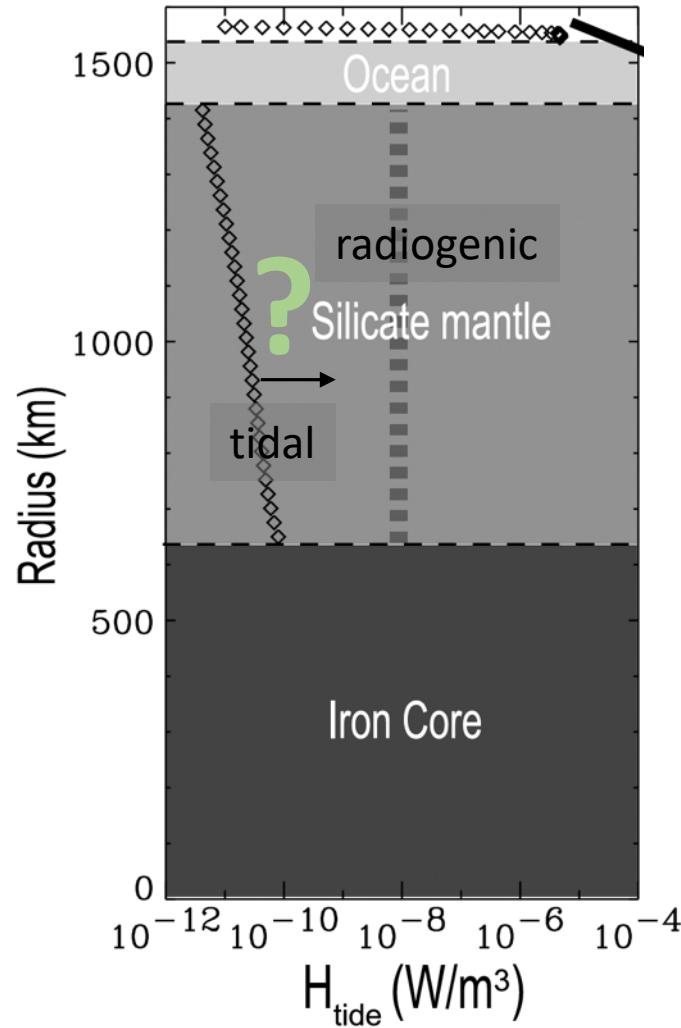


Baptiste Journaux

Backup

Mantle Convection

- Europa's “mantle” is heated internally
 - Radiogenic: by U, Th, K \rightarrow H $\sim 10 \text{ mW m}^{-2}$ or $Q_r \sim 300 \text{ GW}$
 - Tidal: $Q_c \sim 0.1 \text{ GW}$ (Tobie et al. 2003)
 - Assumes Earth's mantle viscosity $\eta=10^{21} \text{ Pa s}$
 - In fact, in Earth's upper mantle, $\eta=10^{19} \text{ Pa s}$ (Sacek et al. 2013)
 $\rightarrow Q_c$ may be closer to Q_r
- Even a radiogenic thermal profile encounters melt
 \rightarrow Solid state convection may be the norm for Europa's mantle



(modified from
Tobie et al. 2003)

Loss of Europa's Water to Space

Neutral H₂O sputtering by radiation

globally $\sim 2 \times 10^{27}$ molecules s⁻¹

22% of this is lost to space

(Plainaki et al. 2010, Teolis et al. 2017)

O+ and O₂ loss dominated by charge exchange, $> 7 \times 10^{26}$ s⁻¹

(Lucchetti et al. 2016)

Annually

That's 0.4 Gmol yr⁻¹

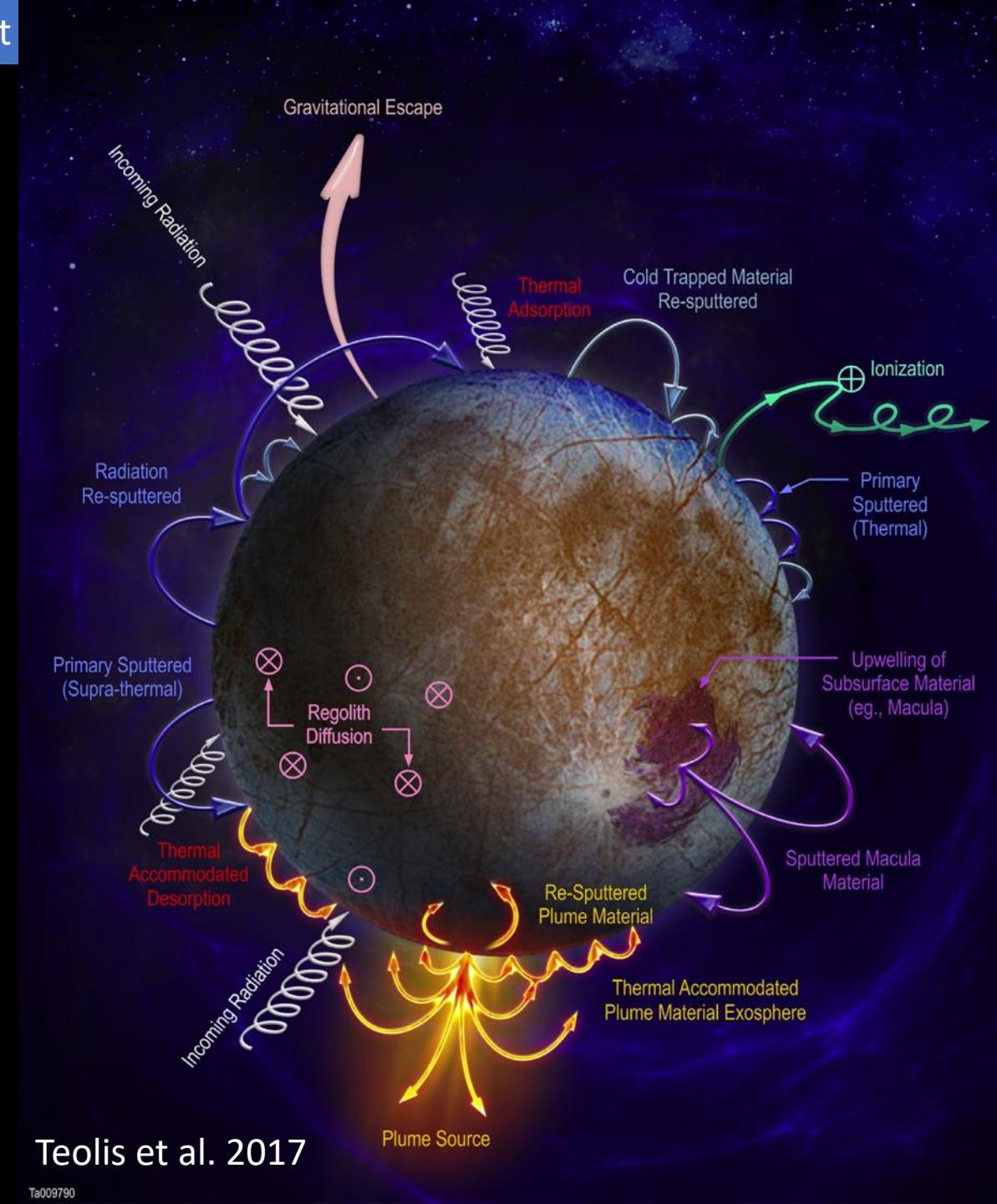
Over 100 Myr (~Europa's surface age)

That's 1.5 m of material

(Plainaki et al. 2010 estimate 0.7 m)

Over 4 Gyr

0.003% of Europa's mass,
or $\sim 0.06\%$ of a 100 km-thick water covering
or about 59 m material



Teolis et al. 2017

Loss of Europa's Water to Space

Loss through cryovolcanism

H_2O loss comparable to the Enceladus plume:

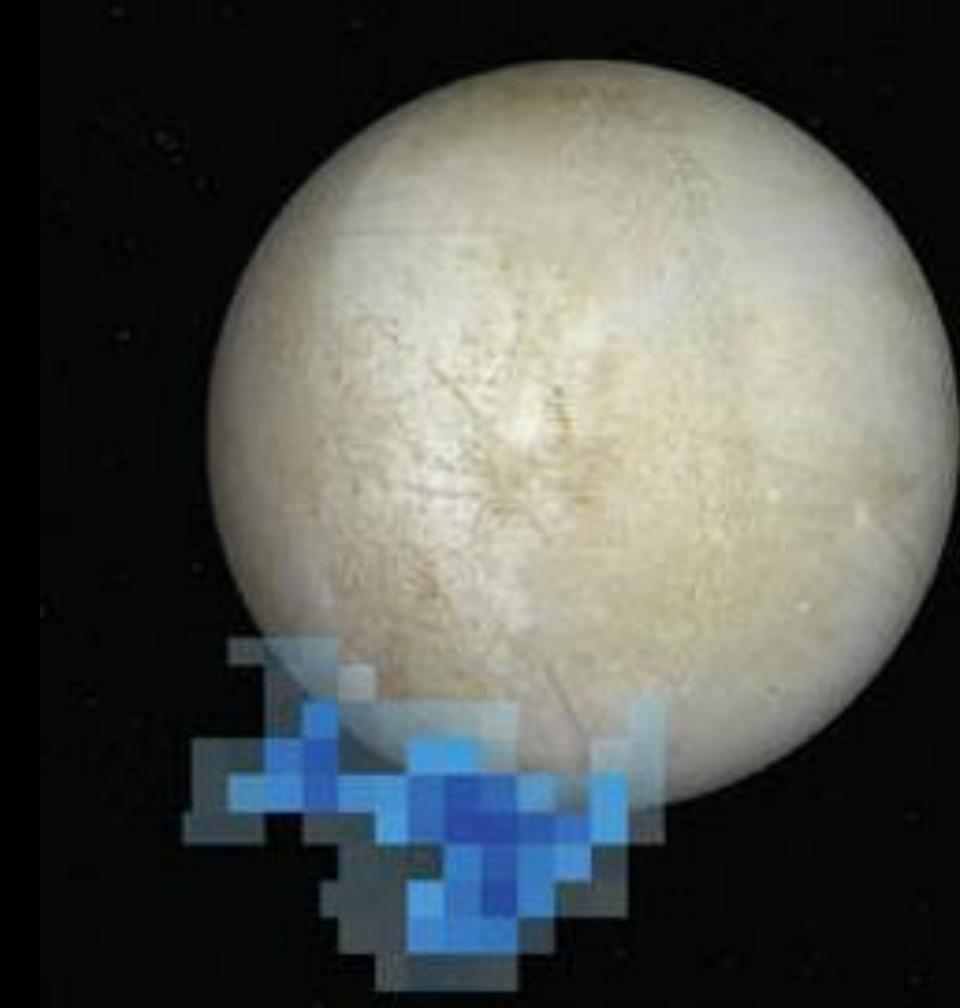
200 kg s^{-1} (Hansen et al. 2011)

assume all is lost to space

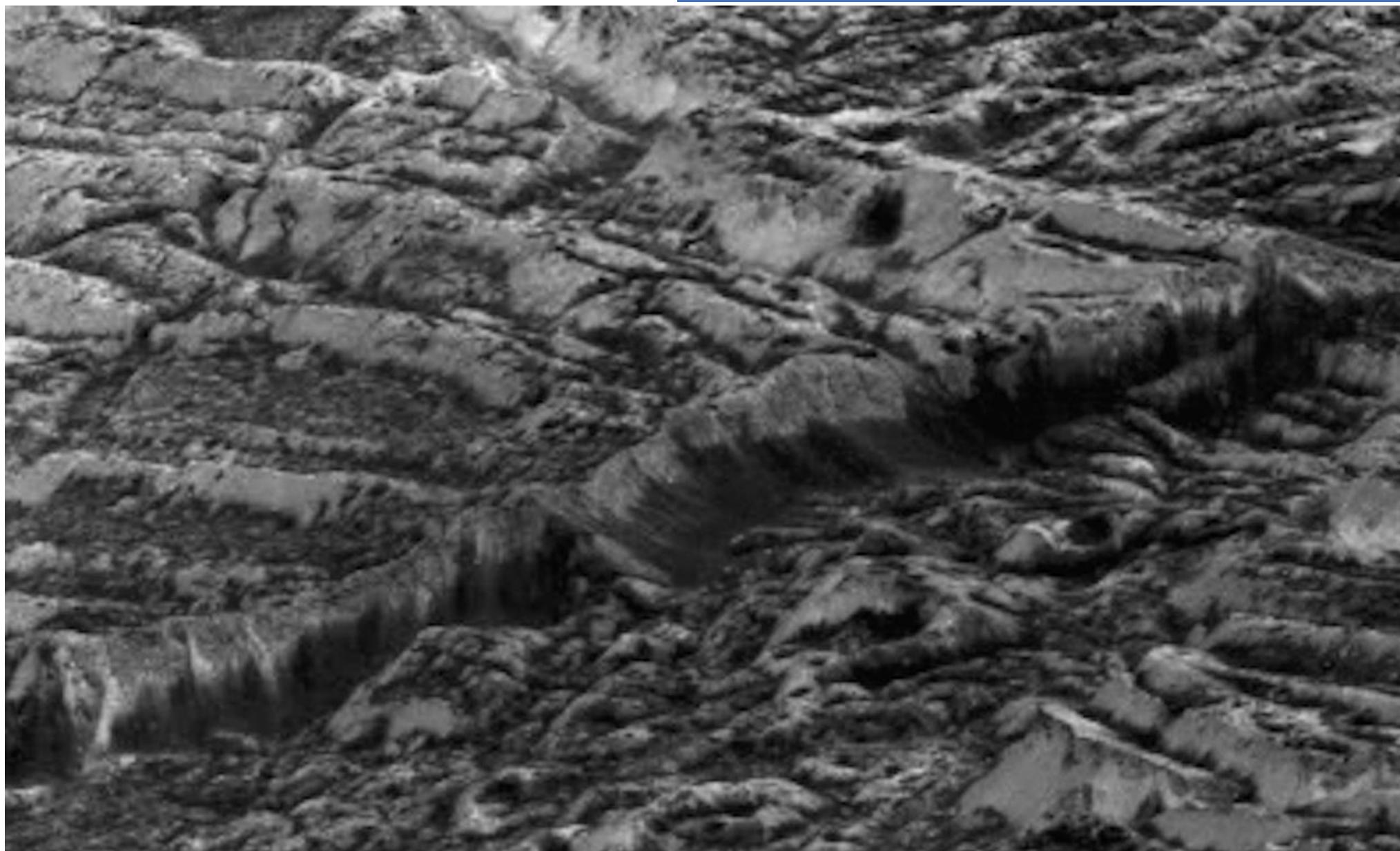
Over 4 Gyr

0.05% of Europa's mass

However, most of this should return to the surface
under Europa's gravity (e.g., Fagents 2000)



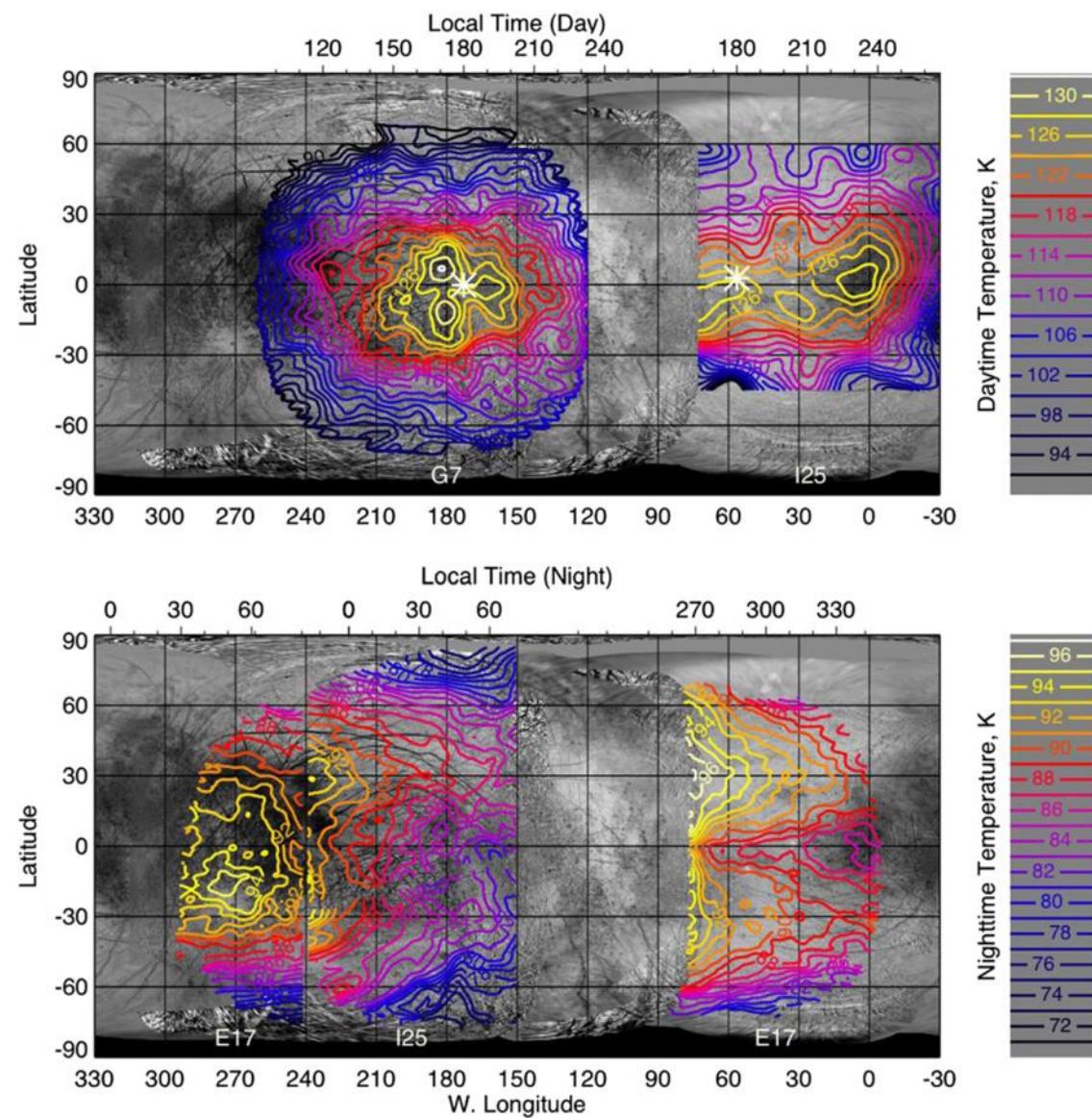
After Roth et al. 2014



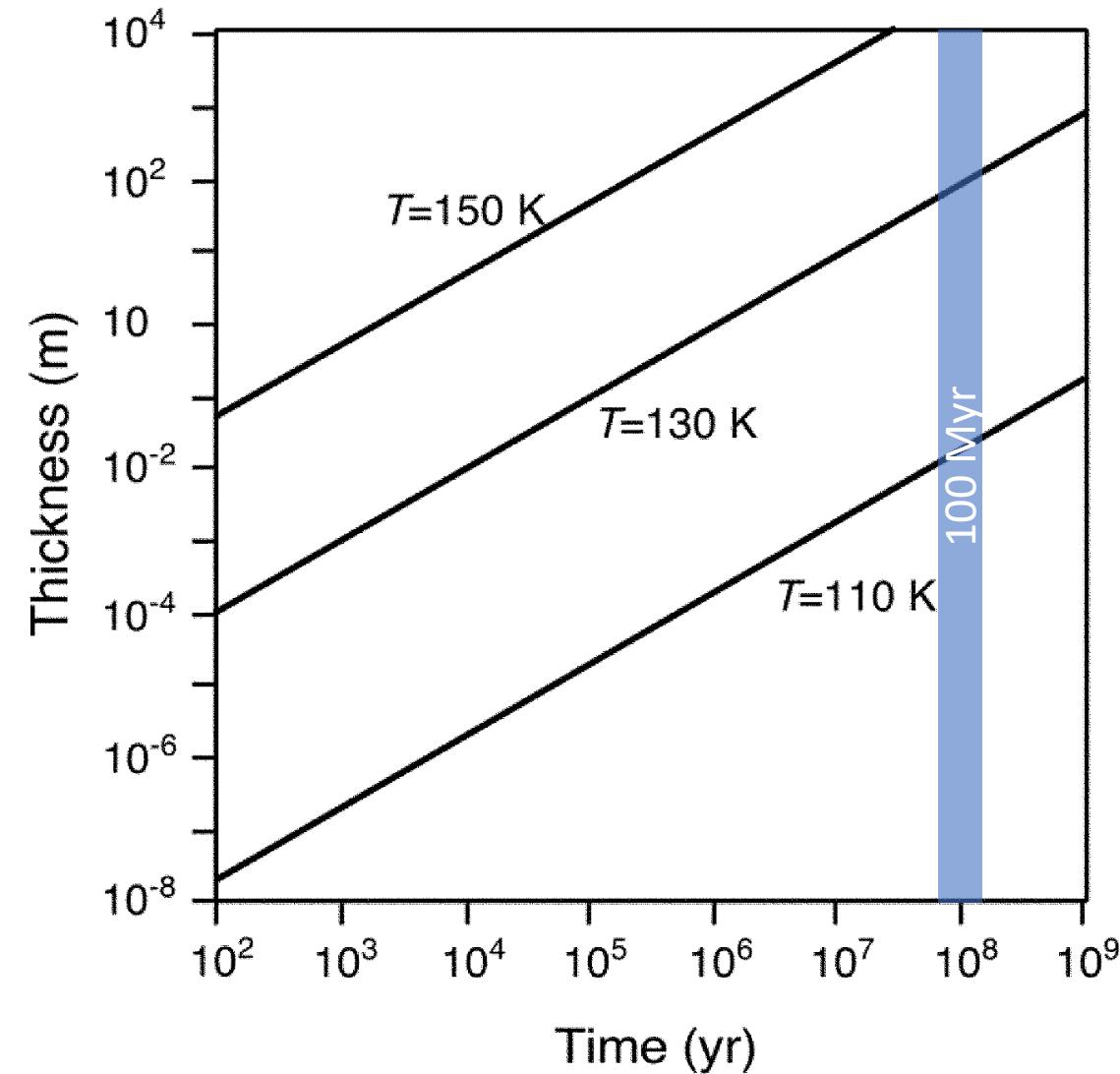
12 m/pixel

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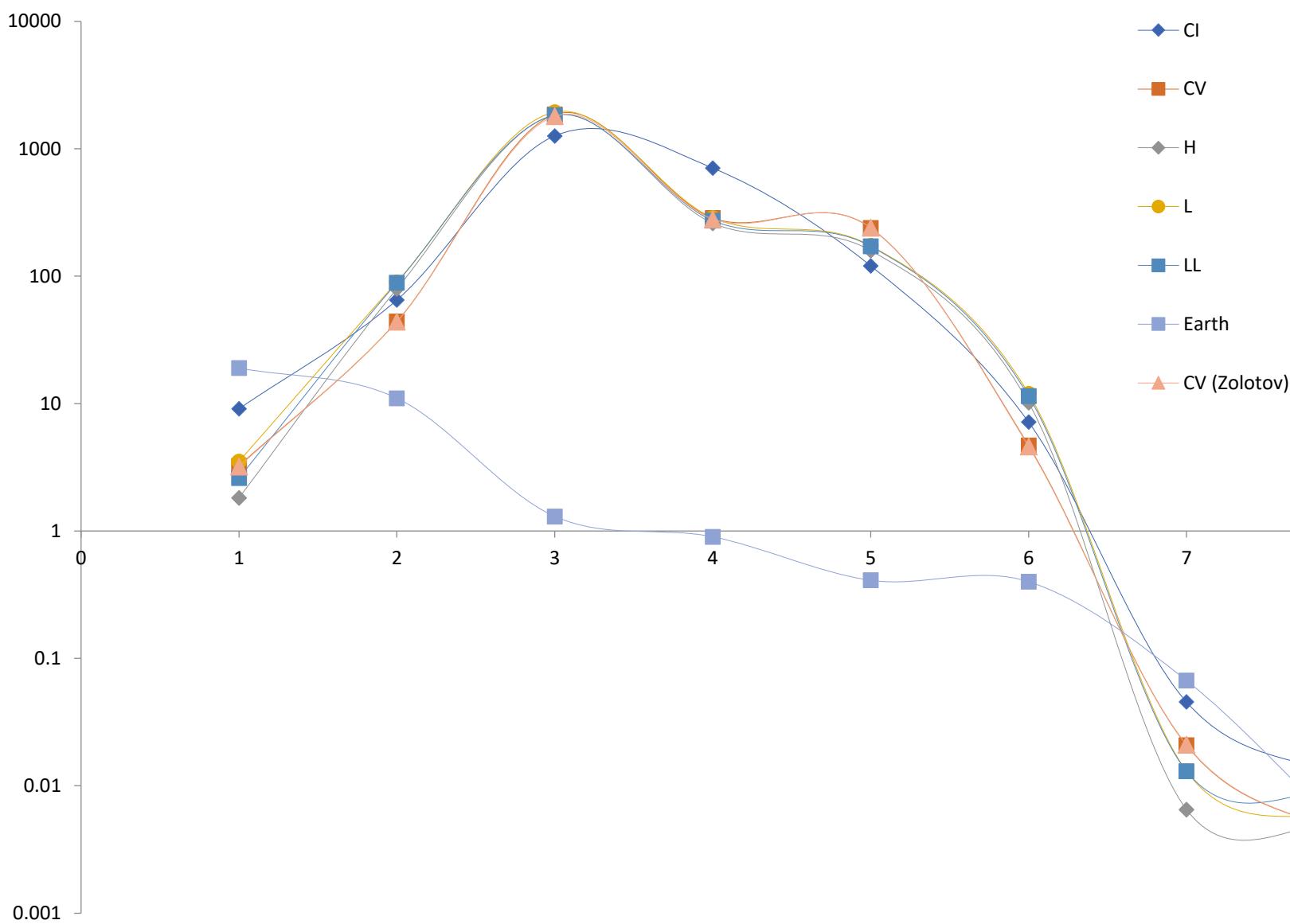
Thermal desorption into the atmosphere



Spencer et al. 1999, Rathbun et al. 2010

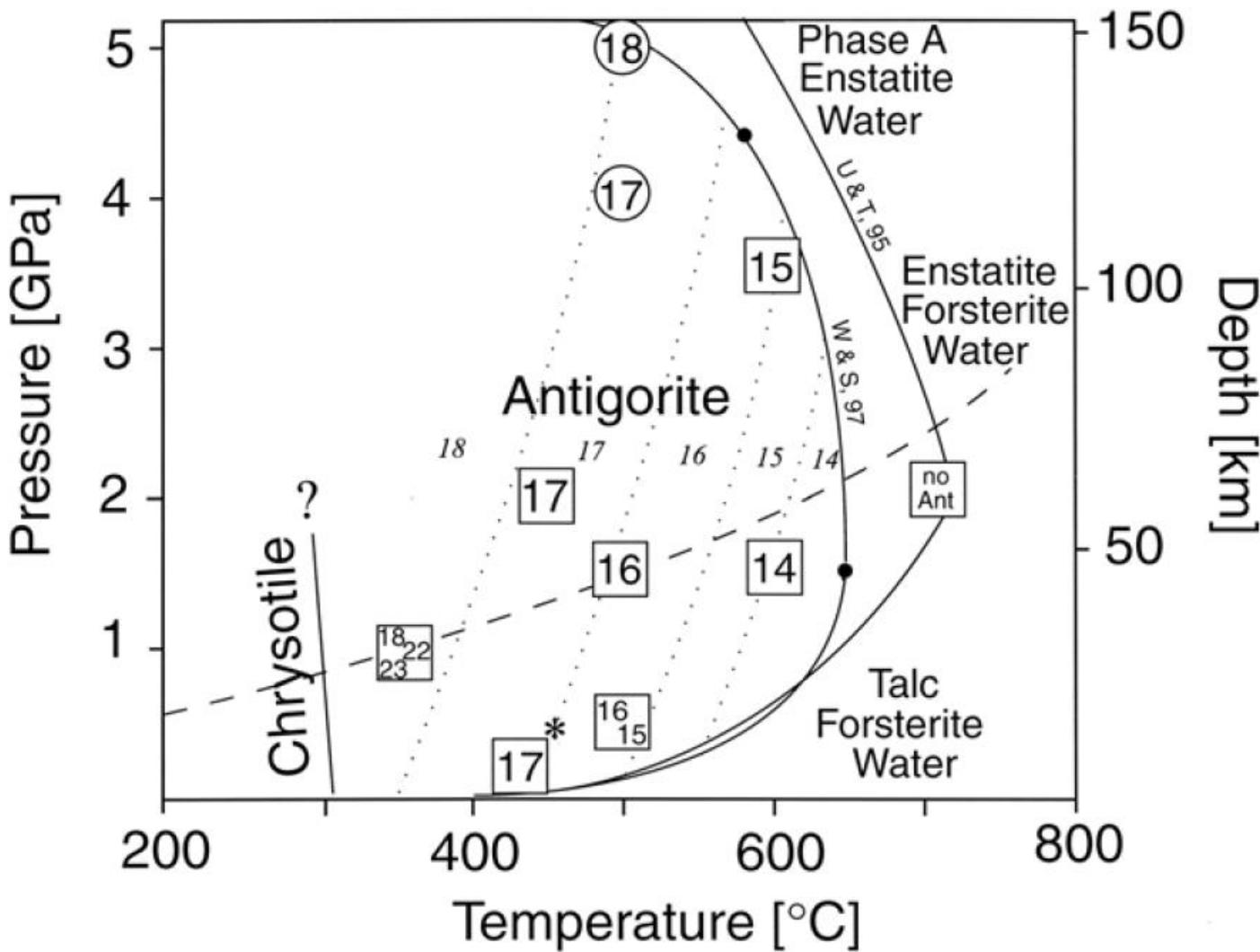


Fagents et al. 2010



Delivery of Water from Space

Water from comets (Zahnle et al. 2003)



Wunder et al. 2001

Earth's core may contain most of its sulfur

